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AN EXPERIMENTAL AND ANALYTICAL STUDY OF SPECTRUM TRUNCATION EFFECTS

J. M. POTTER

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AFFDL-TR-73-117

AN EXPERIMENTAL AND ANALYTICAL STUDY OF SPECTRUM TRUNCATION EFFECTS

J. M. Potter

FOREWORD

At the request of the B-1 Systems Program Office, a test and analysis program was performed to evaluate the effects of spectrum truncation using representative flight-by-flight load histories. The results of the experimental program are herein presented and correlated with the Sequence Accountable Fatigue Analysis computer program.

The testing was accomplished by the Experimental Branch, Structures Division under Project 139A, Task 0501. Mr. H. Stalnaker was Project Engineer. Dr. V. Venkayya and Ms. V. Tischler of the Solid Machanics Branch, Structures Division, performed the finite element analysis of the coupon. Mr. R. A. Noble and L. J. Reed assisted significantly in the development of the correlation analyses.

This report was submitted by the author in September 1973.

This report has been reviewed and is approved.

FRANCIS J. JANIK, Jr.
Chief, Solid Mechanics Branch
Structures Division

ABSTRACT

A series of flight-by-flight fatigue tests was conducted to evaluate the fatigue behavior of simple structural components as a function of the degree of spectrum truncation. The levels chosen for truncation were those that gave no fatigue damage according to a conventional fatigue analysis. The fatigue test data indicated that the full spectrum resulted in the shortest life in terms of flights, and the life increased as more low-level cycles were truncated. The results are compared to predictions made using both conventional analyses and the Sequence Accountable Fatigue Analysis. The conventional fatigue analysis was calculated in two variations, with and without the range-pair counting method. Both conventional predictions were very unconservative and did not predict the fatigue behavior trends. The Sequence Accountable Fatigue Analysis, however, does fit the data adequately and indicates the trends. The data and the correlation with this sequence-sensitive analysis indicate that residual stresses and residual stress relaxation play a major role in the determination of structural fatigue life.

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SECTION I

INTRODUCTION

Life testing of aircraft or large components of aircraft has always been a complicated and long-drawn-out process. It has also been extremely expensive, in part because of the thousands of manhours required to complete the testing. We realized that considerable savings could be realized if the test spectrum could be simplified and the low-level cycles truncated. The situation has been complicated by the fact that there is normally only one article, or at most two, available for test. Thus, little or no comparison testing could be done, so there could be no basis for determining how the truncation of the test spectrum would affect the results.

Structural engineers have recently found that conventional fatigue damage analyses of structures subjected to spectrum applied load histories do not provide accurate predictions of fatigue behavior. For example, the application of peak positive loads, such as proof stresses, tend to extend the life of the structure rather than shorten it, as would be expected intuitively. Further, Heywood (Reference 1) and Rosenfeld (Reference 2) report that the higher the proof stress to which the structure is subjected, the longer the subsequent life of the structure. Moreover Mordfin and Halsey (Reference 3) and Potter (Reference 4) report that repeating the proof stress periodically during the structure's lifetime resulted in further extending it. These data indicate that there are sequence-dependent as well as cycle-dependent residual stress effects in the fatigue behavior of component structures.

This report presents the results and analysis of a series of tests designed to investigate the effects of load cycle truncation in a flight-by-flight sequence loading. Conventional damage analyses were used to determine the load cycles that could be eliminated without significantly changing the structural life when compared to the full spectrum. A newly developed cumulative damage analysis, the Sequence Accountable Fatigue Analysis, was used to make independent predictions of the truncation.

SECTION II

TEST CONDITIONS

1. LOAD SPECTRA AND TRUNCTION CRITERIA

Three load spectra were used in this truncation study; these spectra were prepared and supplied by the manufacturer of the B-1 aircraft, Rockwell International, hereinafter referred to as RI/B-1. The basic life test spectrum contained approximately 1,463,000 cycles per 1280 flights, and the two truncated spectra contained 270,000 cycles and 135,000 cycles per 1280 flights. Hereafter in this report, these spectra will be referred to as the 1463K, the 270K, and 135K spectra.

The basic spectrum represented the stress history of the B-1 aircraft at the lower surface of the wing pivot, at location XRS 188. These truncation levels were chosen because they were determined to be "non-damaging" according to an analysis of the spectrum loads performed by RI/B-1, using a conventional fatigue analysis. This fatigue analysis was of the type where the damage is calculated from a simple $\Sigma n/N$ procedure, where n is the number of applied cycles at a nominal stress level based on the nominal load history, and N is the constant amplitude life of a similarly configured coupon at that same applied stress. The nominal stress history was range-pair counted prior to damage calculation. The three spectra are presented in Table I. Note that in this truncation technique, the highest levels, the stress ranges, and the spectrum order are not changed for the three test spectra.

2. SPECIMENS

Notched specimens of 2219-T851 aluminum, such as is used for the B-1 structure, were supplied by RI/B-1 to the Air Force Flight Dynamics Laboratory for testing. The specimen configuration is shown in Figure 1. The plastic stress concentration factor was specified as 4.5 based on the net stress. An elastic finite element analysis was conducted which verified this value.

TABLE I

SPECTRA USED IN SPECTRUM TRUNCATION TESTS

LOAD LEVELS IN PERCENT OF LL*			CYCLES PER LOAD LEVEL		
STEP	MAXIMUM LOAD	MINIMUM LOAD	1463K	270K	135K
1	-2.9	-14.8	1	1	1
2	100.	58.4	One cycle every 100 flights		
3	89.5	58.4	One cycle every 10 flights		
4	68.4	58.4	2	1	1
5	58.4	45.5	2	1	1
6	69.3	64.8	2	1	1
7	69.9	39.5	1	1	1
8	56.3	48.8	29	3	3
9	50.9	23.5	1	1	1
10	62.7	50.9	22	2	2
11	50.9	43.4	22	1	1
12	69.0	36.4	1	1	1
13	36.4	13.3	1	1	1
14	48.2	36.4	58	6	6
15	36.4	30.4	58	1	1
16	75.6	30.7	1	1	1
17	52.7	31.6	1	1	1
18	70.8	54.5	One cycle every 10 flights		
19	61.7	33.4	1	1	1
20	51.2	40.1	7	7	1
21	54.8	12.7	1	1	1
22	37.7	22.9	132	48	6
23	34.0	-0.6	1	1	1
24	24.4	13.0	132	35	4
25	72.3	7.8	1	1	1
26	55.7	11.1	9	9	9
27	37.7	18.7	95	10	10
28	99.1	52.7	One cycle every 100 flights		
29	88.3	-12.0	One cycle every 10 flighs		
30	74.7	52.7	1	1	1
31	-2.9	-14.8	1	1	1
32	84.6	55.7	1	1	1
33	88.0	50.9	1	1	1
34	52.7	33.1	1	1	1
35	61.7	52.7	19	19	2
36	52.7	46.4	19	2	1
37	81.0	48.2	1	1	1
38	68.7	58.1	4	1	1
39	70.2	32.2	1	1	1
40	44.9	39.5	9	9	1
41	59.0	43.1	48	5	5
42	54.5	46.1	294	29	29
43	-2.9	-14.8	8	1	1
44	-3.9	-13.6	154	1	1

*Limit stress level

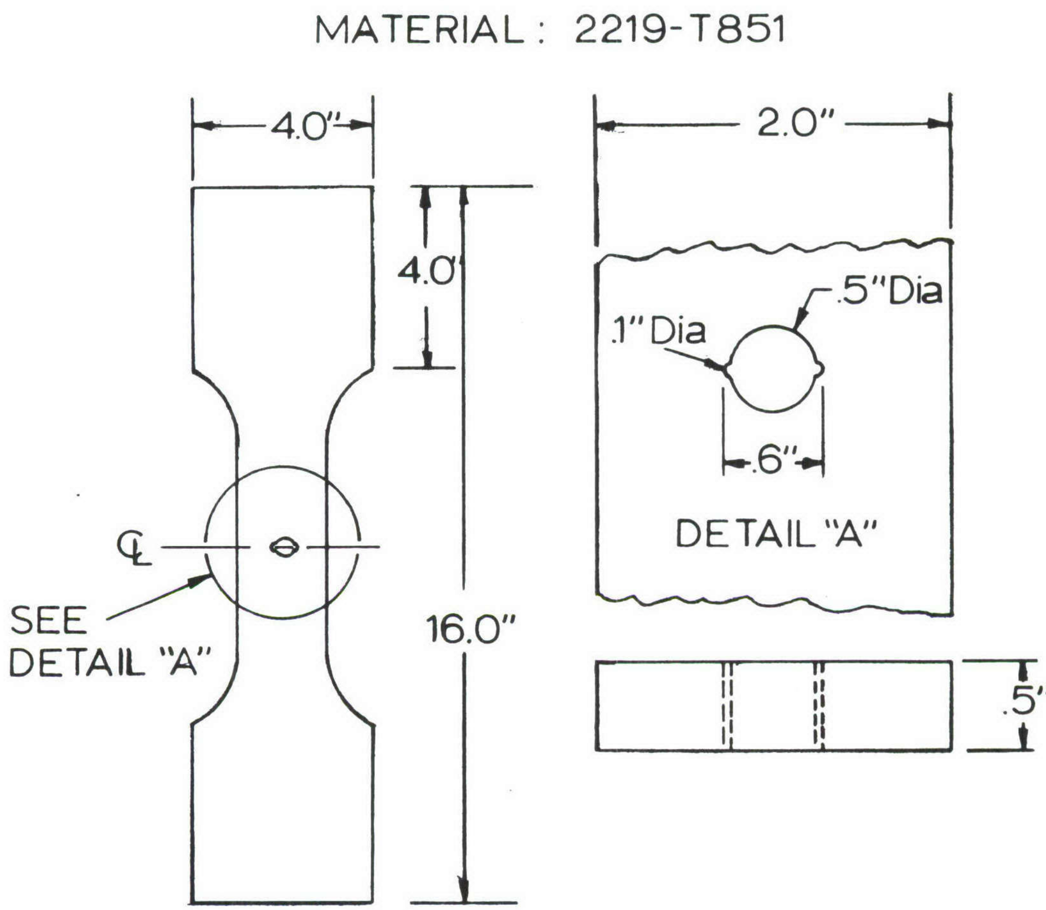


Figure 1. Specimen Geometry Used in the Spectrum Truncation Study

3. STRESS LEVEL

RI/B-1 supplied the Systems Program Office with a set of fatigue life predictions as a function of limit stress level (LL). A target life of 2500 flights was arbitrarily established by that office as the value needed to verify the RI/B-1 truncation analysis. The limit stress level to produce 2500 flights of life was predicted to be 33.6 ksi, based on the RI/B-1 conventional analysis. After three tests were completed, however, the limit stress level to obtain the target life was reduced to 80% of that value, or 26.9 ksi, based on preliminary calculations by the author.

SECTION III
TEST RESULTS

The results of the fatigue tests performed by AFFDL/FBT are summarized in Table II. The time when a visible crack was detected is a fairly arbitrary value, and so the number of flights indicated under the "Visible Crack" column of Table II is more an indication of the intuition and observation power of the viewer than a measurable quantity. The value shown is the time when two or more observers agreed that a crack existed along the inside hole; it thus could be considered a "committee" sized crack.

The number of flights required to attain the various crack lengths is more accurate. Crack lengths were measured at each side of the hole using a 40-60X microscope with a 0.005-inch calibrated Mylar tape attached to the surface, and were estimated to be accurate to within 0.003 inch. The numbers of flights given for the various crack lengths are averages of the number of flights needed to made the sum of the right and left-hand cracks equal to 0.10, 0.125, 0.15, and 0.20 inch. These values are accurate to ± 5 flights.

The data indicate a definite uniform tendency for the number of flights to visible crack initiation, to average values of surface crack lengths, and to separation of the coupon to increase as the truncation level changes from the 1463K to the 135K spectra.

TABLE II

EXPERIMENTAL RESULTS

Truncation Level Cycles per 1280 Flights	Limit Load Stress (ksi)	Spec No.	Number of Flights to Crack Lengths (in inches) or Separation					
			Visible Crack	0.1	0.125	.150	.20	Separation
1463K	33.6	36-56	100	345	363	375	397	406.5
270K	33.6	36-61	200	470	497	516	545	568.7
135K	33.6	36-55	250	458	481	503	537	561.7
1463K	26.9	36-62	375	670	710	740	795	875.5
1463K	26.9	36-58	320	770	820	850	907	973.5
1463K	26.9	36-53	285	805	835	867	907	975.5
Average			326.6	748	788	819	870	941.5
270K	26.9	36-63	250	990	1040	1070	1120	1216.6
270K	26.9	36-57	455	1025	1065	1100	1165	1250.7
270K	26.9	36-64	350	1120	1175	1215	1295	1410.5
Average			351.3	1045	1095	1130	1195	1292.6
135K	26.9	36-59	500	920	980	1035	1100	1188.0
135K	26.9	36-54	400	1115	1165	1215	1295	1411.6
135K	26.9	36-60	600	1204	1225	1304	1380	1496.7
Average			500	1080	1125	1185	1260	1365.4

SECTION IV

ANALYTICAL CORRELATION

Predictions for the fatigue life resulting from the spectra were made by means of the Sequence Accountable Fatigue Analysis and the Conventional Fatigue Analysis computer programs. Both programs were developed in-house in the Structures Division of the Air Force Flight Dynamics Laboratory to analyze the fatigue behavior of structures with any general applied load spectrum. The details of the Sequence Accountable Fatigue Analysis are presented in Reference 5. This program predicts the accumulated damage by calculating the local stress and strain history at a notch in a structural member. This analysis includes a calculation of the local plastic strain excursions associated with the creation of residual stresses and the resulting elastic local stress cycles during the spectrum. Damage is calculated and accumulated for both the elastic local stress and the plastic local strain cycles. The local elastic stress spectrum is range-pair counted prior to damage accumulation. The residual stress relaxation analysis of Potter (Reference 4) is included in the program. The primary effect of the residual stress relaxation is to change the damage accumulation rate of the cycles following the peak loads, but it also affects the plastic strain experienced during the peak loads.

The Sequence Accountable Fatigue Analysis program has but one significant unknown variable when the specimen geometry, S-N data, and spectrum are sufficiently described, as is the case in these truncation effects studies. That unknown variable is the rate of residual stress relaxation. The residual stress relaxation function derived by Potter (Reference 4) and that by Impellizzeri (Reference 6) are estimates of the relaxation behavior and are based on fatigue life data rather than measured residual stress behavior. The Potter residual stress relaxation function is:

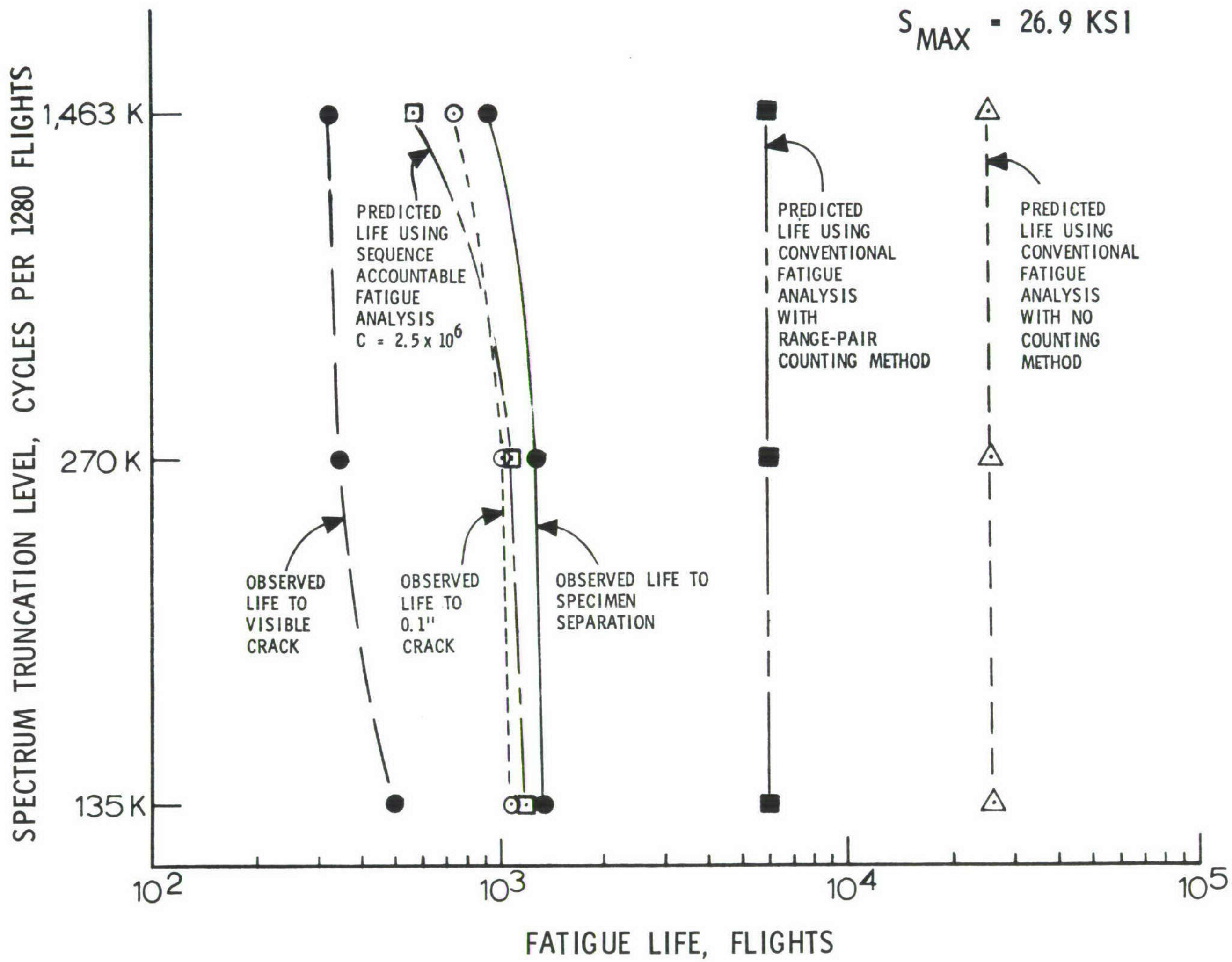
$$\sigma_{TRANSIENT} = (\sigma_R - \sigma_{R_{EQ}})\ \mathrm{EXP}\left[N(K_t S_{MAX})^m (K_t S_{MEAN})^n \ln(0.1)/C\right]$$

where

σ_R	residual stress
$\sigma_{R_{EQ}}$	equilibrium value of the residual stress; that value that would exist had there been no previous history
$\sigma_{TRANSIENT}$	Residual stress component that changes as a function of applied cycles
N	number of cycles
K_t	elastic stress concentration factor, based on net section
S_{MAX}	maximum stress level in a block, based on net section
S_{MEAN}	mean stress level in a block, based on net section
m, n	residual stress relaxation exponents, m=n=1.
C	residual stress relaxation constant

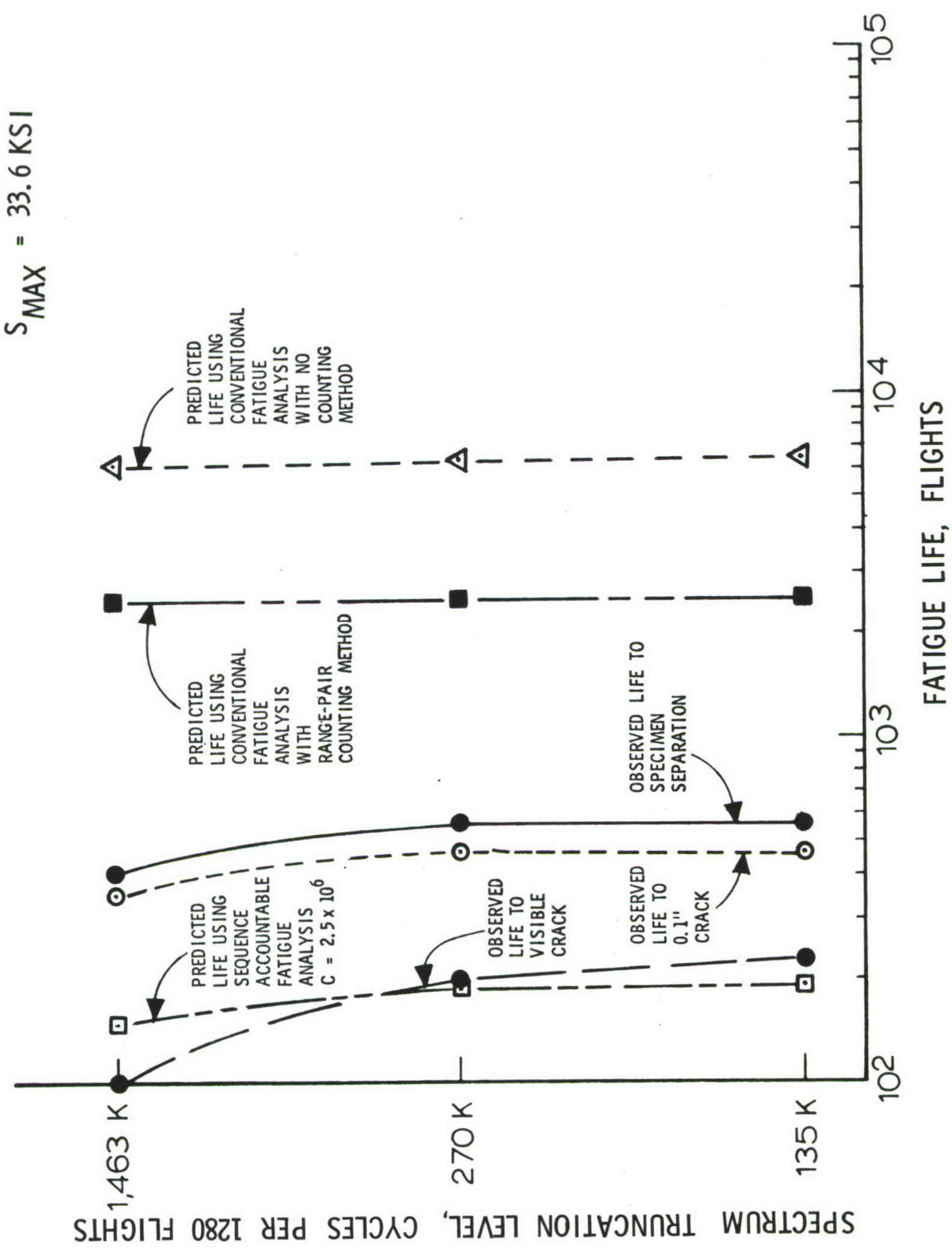
Predictions of life were made for values of the residual stress relaxation constant, C, over a range of expected values. The residual stress relaxation constant can be estimated in the range of $10\text{-}20 \times 10^6$ (cycles) $(\text{ksi})^2$ from data presented by Potter (Reference 4). The S-N data from unnotched coupons of 2219-T851 aluminum was supplied by RI/B-1. The predicted life values are summarized in Table III and compared to measured fatigue lives in Figure 2.

As a check on the predictions that would be made using more conventional analyses, a parallel computer program called the Conventional Fatigue Analysis was developed. This determines fatigue damage using the elastic stress history and calculates the damage from the notched coupon S-N data. In the program the stress history is calculated and range-pair counted, and the damage is determined from the range-paired stress spectrum. The S-N data for K_t = 4.5 notched coupons of 2219-T851 was supplied by RI/B-1. The Conventional Fatigue Analysis with the range-pair counting method is essentially the same as the analysis used by RI/B-1. Results predicted with the Conventional Fatigue Analysis are within 5% of those predicted by RI/B-1 for the same limit load stresses.



a. Load Level at 26.9 ksi

Figure 2. Comparisons of Observed and Predicted Fatigue Life Behavior



b. Load Level at 33.6 ksi

Figure 2. Comparisons of Observed and Predicted Fatigue Life Behavior.

To illustrate the effect of the range-pair counting method on the fatigue life prediction, the same damage accumulation prediction was made without range-pair counting. The resulting predictions are also presented in Table III. The predictions and the results are summarized in Figure 2.

The pertinent relations used in the two fatigue analyses are presented in Appendix I.

TABLE III

FATIGUE BEHAVIOR PREDICTIONS

TEST PARAMETERS		FATIGUE LIFE PREDICTIONS, FLIGHTS									
		CONVENTIONAL FATIGUE ANALYSIS		SEQUENCE ACCOUNTABLE FATIGUE ANALYSIS							
LIMIT STRESS LEVEL, ksi	TRUNCATION LEVEL, CYCLES PER 1280 FLIGHTS	WITH RANGE PAIR COUNTING METHOD	WITH NO COUNTING METHOD	RESIDUAL STRESS RELAXATION CONSTANT, X 10^6 Cycles $(ksi)^2$							
				20	10	5	2.5	1.25	.625	.3125	.15625
33.6	1463K	2500	6200	190	190	180	150	110	70	55	50
	270K	2500	6400	180	180	190	190	180	150	110	80
	135K	2500	6400	180	180	180	190	190	190	150	110
26.9	1463K	6000	25,000	1200	1100	740	580	410	290	210	170
	270K	6000	26,000	1200	1200	1200	1100	950	630	460	310
	135K	6000	26,000	1200	1200	1200	1200	1100	830	630	470

SECTION V

CORRELATION OF EXPERIMENTAL DATA WITH THE ANALYTICAL PREDICTIONS

The data presented in Table II indicate these simple notched structures display significant differences in fatigue behavior with the applied spectra. These differences reflect the inadequacy of the original cumulative damage analysis to predict the significance of the load levels selected for truncation. There is a uniform tendency for the fatigue behavior trends to increase with truncation level from the 1463K full spectrum to the 135K truncated spectrum.

These tests point out the potential hazards of truncating on the basis of eliminating cycles because little or no damage was ascribed to them in an elastically based analysis. Were these truncated test results used to predict the full spectrum test life they would be unconservative. At the 26.9 ksi level, the full spectrum article lasted 68.9% of the number of flights determined in the 135K spectrum, and 72.8% of those determined in the 270K spectrum.

The predictions using the Conventional Fatigue Analysis show practically no effect of the truncation level and were very unconservative as well. The results with and without the range-pair counting method are similar. Note that the conventional analysis, even with the range-pair counting method, predicts only a minor variation in fatigue life as a function of the truncation level.

The predictions obtained from the Sequence Accountable Fatigue Analysis display trends similar to that produced in the experimental results. A residual stress relaxation constant of 2.5×10^6 (cycles) $(\text{ksi})^2$ correlates best with the trends of the measured data. Physically, the residual stress relaxation constant is directly proportional to the number of cycles required to relax the value of the history-dependent residual stress. Therefore, the higher the residual stress relaxation constant, the more stable is the residual stress. The results

of this can be seen at the residual stress relaxation constant of 20×10^6, where there is practically no difference in fatigue life with truncation level.

Figure 3 consolidates the effect of the residual stress relaxation constant on fatigue life for the three spectra and two stress levels used. These data are plotted directly from information presented in Table III. Figure 3 indicates that, for these spectra, longer life results from a more stable residual stress. An upper limit in fatigue life is seen for higher values of the residual stress relaxation constant. This upper limit coincides with the value of fatigue life that would result from an analytical prediction method that included residual stresses but not residual stress relaxation. This upper limit, interestingly enough, coincides with the lower limit in fatigue life predictions that would result from an analytical prediction that included residual stresses and a mean stress relaxation model such as that proposed by Morrow, et al (Reference 7). If a mean stress relaxation model had been included in this basic fatigue analysis instead of the residual stress relaxation model, the 1463K spectrum would give the longest life with the 135K spectrum giving the shortest life. Note that this behavior is completely opposite to the observed fatigue life behavior. Faster mean stress relaxation would result in further discrepancies with the observed fatigue life behavior.

The correlation of the Sequence Accountable Fatigue Analysis predictions with the measured data supplies additional empirical evidence that residual stress relaxation occurs and is a significant factor in the fatigue performance of spectrum loaded structures. A detailed examination of this analysis indicated that the levels that were truncated actually caused little damage by themselves. The significance of these levels to the resultant fatigue behavior according to the Sequence Accountable Fatigue Analysis is that they allow the beneficial residual stresses to relax causing a magnification of the damage from the larger cycles which follow.

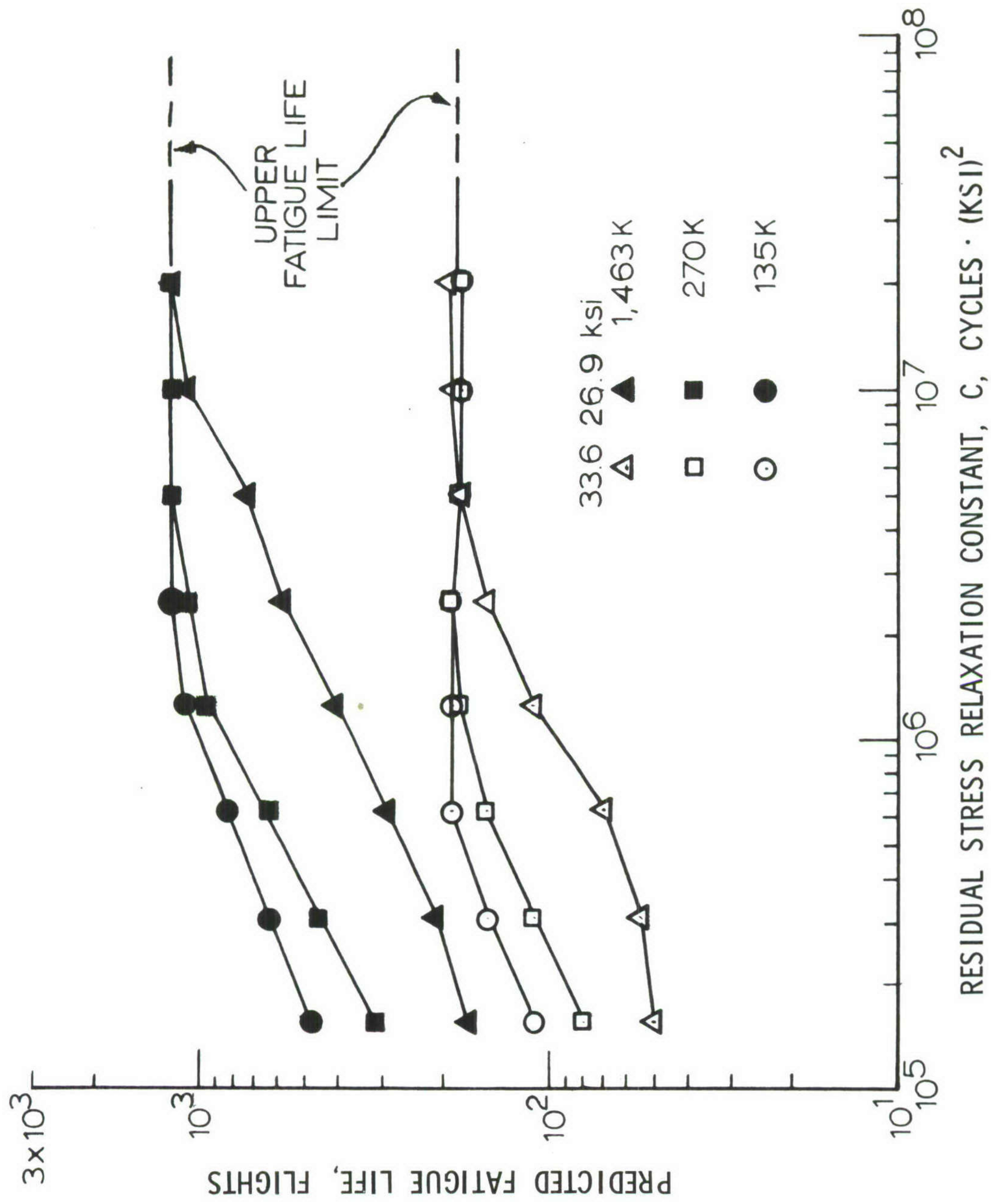


Figure 3. Effect of Varying the Residual Stress Relaxation Constant on the Fatigue Life Prediction

The accuracy of the predictions made using the Sequence Accountable Fatigue Analysis compared to those of the Conventional Fatigue Analysis is not accidental. Many existing state-of-the-art analyses tend to use a simple technique, such as the fatigue concentration factor or weighted counting methods, to trick or force a usually admittedly inaccurate and physically incorrect material behavior model into giving the desired answers. The Sequence Accountable Fatigue Analysis develops its fatigue damage model by synthesizing into a single analysis the effects and damage contributions of elastic stresses as well as plastic strains. In the predictions made for the 26.9 ksi tests, for instance, fully 40% of the damage was due to plastic strains with the elastic stress damage providing the remainder. An analysis ignoring either the damage associated with plastic strains or elastic stresses must be rather severely forced by large increases in the fatigue concentration factor or modification in the counting method to make up the difference in damage.

The residual stress relaxation constant and in fact the relaxation function remain mysterious quantities. More accurate and more general fatigue life predictions will be possible when this behavior is measured and quantified. Techniques of residual stress measurement using X-ray diffraction would be useful in determining the actual behavior.

SECTION VI

CONCLUSIONS

1. Conventional fatigue analysis techniques cannot adequately describe structural fatigue behavior or behavior trends under spectrum conditions.

2. Unless truly sequence-sensitive analyses are used, severely truncated spectra should not be applied to critical life verification tests of structural components.

3. The Sequence Accountable Fatigue Analysis can adequately describe the fatigue behavior of notched structural components under spectrum load conditions. Prior to more extensive use of this analysis the residual stress relaxation behavior should be more satisfactorily described by actual measurements.

APPENDIX

1. MATERIAL DATA USED IN THE SEQUENCE ACCOUNTABLE FATIGUE ANALYSIS

Material Type	2219-T851
Stress Concentration Factor (Elastic)	4.5
Tensile Yield Stress (assumed flat top yield)	55. ksi
Low-Cycle Fatigue Intercept	0.4 in/in
Slope of Plastic Strain-Life Relation	-0.536

Unnotched Coupon S-N Data

COEFFICIENTS OF SECOND ORDER LEAST SQUARE FIT OF S-N DATA
SMAX = A(I)*SMIN**2 + B(I)*SMIN + C(I)

LIFE	A(I)	B(I)	C(I)
10** 4	-.00217	.220	55.8
10** 5	-.00178	.332	48.2
10** 6	-.00149	.462	39.6
10** 7	-.00243	.641	31.7

2. MATERIAL DATA USED IN THE CONVENTIONAL FATIGUE ANALYSIS

Material Type	2219-T851
Stress Concentration Factor (Elastic)	4.5

Notched Coupon S-N Data

COEFFICIENTS OF SECOND ORDER LEAST SQUARE FIT OF S-N DATA
SMAX = A(I)*SMIN**2 + B(I)*SMIN + C(I)

LIFE	A(I)	B(I)	C(I)
10** 4	.00535	.480	30.8
10** 5	.00434	.607	18.4
10** 6	.00359	.695	11.5
10** 7	.00323	.713	9.4

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13. ABSTRACT

A series of flight-by-flight fatigue test was conducted to evaluate the fatigue behavior of simple structural components as a function of the degree of spectrum truncation. The levels chosen for truncation were those that gave no fatigue damage according to a conventional fatigue analysis. The fatigue Test data indicated that the full spectrum resulted in the shortest life in terms of flights, and the life increased as more low-level cycles were truncated. The results are compared to predictions made using both conventional analyses and the Sequence Accountable Fatigue Analysis. The conventional fatigue analysis was calculated in two variations, with and without the range-pair counting method. Both conventional predictions were very unconservative and did not predict the fatigue behavior trends. The Sequence Accountable Fatigue Analysis, however, does fit the data adequately indicates and the trends. The data and the correlation with this sequence-sensitive analysis indicate that residual stresses and residual stress relaxation play a major role in the d determination of structural fatigue life.

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Fatigue Test						
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Truncation						
Aircraft						
Structures						
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